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Snow avalanches, land use changes, and atmospheric warming in landscape dynamics of the Atlantic mid-mountains (Cantabrian Range, NW Spain)

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ABSTRACT

The repercussions of snow avalanches, land use changes, and atmospheric warming on landscape dynamics are very important in Atlantic mid-mountains but have received little research attention in comparison to other zones and types of ecological processes. Snow avalanche disturbance have been studied without being to other aspects such as the abandonment of traditional agrosilvopastoral activities and the amplification of snowfall due to climate change. The main objective is to analyse interactions between snow avalanches, land use change, climatic warming, and their effects on the mid-mountain landscape in the Asturian Central Massif (Cantabrian Range, NW Spain). The applied methodology has involved field work, photointerpretation, geomorphological and phytosociological transects, as well as the analysis of climatic variables. This interdisciplinary combination has been completed with statistical, historical and GIS analysis.

The depopulation and abandonment of traditional productive activities in the Atlantic mid-mountain explains the reduction of grasslands and the spontaneous reforestation of the forest area. However, the effectiveness and intensity of snow avalanches currently prevent the growth and recovery of the forests. Specifically, they affect 173.15 km^2 area of the Asturian Massif. In the Sierra del Aramo 370 ha are deforested by snow avalanches. There is a change in snowiness and in its behaviour (copious snowfall concentrated into storms lasting several days). The mid-mountain is affected by snow avalanches even in mid-latitudes and despite atmospheric warming. The disturbing effects of snow avalanches on the landscape dynamics prevent reforestation favoured by depopulation and changes in land use.

1. Introduction

Snow avalanches are one of the main nival processes that act on the dynamics and evolution of mountain environments around the world (Butler, 1985; Luckman, 1978; Schweizer, Jamieson, & Schneebeli, 2003). They play an important role in both the high and mid-mountain areas of temperate and arctic zones, especially on slopes at an angle of 30 to 50° which allow the accumulation of significant snow cover and, moreover, are susceptible to mobilization. In short, such slopes have a decisive influence on the configuration of the landscape of mountain environments, since they not only enhance the geomorphic processes, but also affect the forest and supra-forest zones of the geoecological belts subjected to their disturbance (Bebi, Kulakowski, & Rixen, 2009; Pattern & Knight, 1994; Rixen, Haag, Kulakowski, & Bebi, 2007).

In Spain, most of the research into snow avalanches has been carried out in the Pyrenees and, to a lesser extent, in the Central Range (Muntán et al., 2009, 2010, 2004; Fernández-Cañadas, 2014; Furdada et al., 1995; Molina et al., 2004; Muñoz, 1988; Muntán, 2012). Not much work has been carried out so far in the Cantabrian Mountains, but two types of research can be distinguished: on the one hand, those of a geomorphological nature (Castañón, 1984; González & Serrano, 2010) and, on the other, those which address the risk and danger of snow avalanches, and are based on newspaper sources (García-Hernández, 2018) or susceptibility maps (Beato Bergua, Poblete Piedrabuena, & Marino Alfonso, 2018). Worthy of mention are the papers on the hazard of avalanches in the Alto Sil (Santos, Redondo, Gómez, & González, 2010), the Central Massif of the Picos de Europa (Vada, Frochoso, & Vilaplana, 2012), and the Alto Carrión (Serrano, Gómez, & Pisabarro, 2016), together with the analysis that addresses the susceptibility and risk of snow avalanches on the San Isidro Massif (Poblete, Beato, & Marino, 2016). However, in no case are the disturbing effects of snow avalanches on ecosystems or landscapes analysed, and most of the studies focus on the high mountain areas of the Cantabrian Mountains, leaving aside the mid-mountains zones, which have not yet been investigated.

In contrast, internationally there is extensive scientific research

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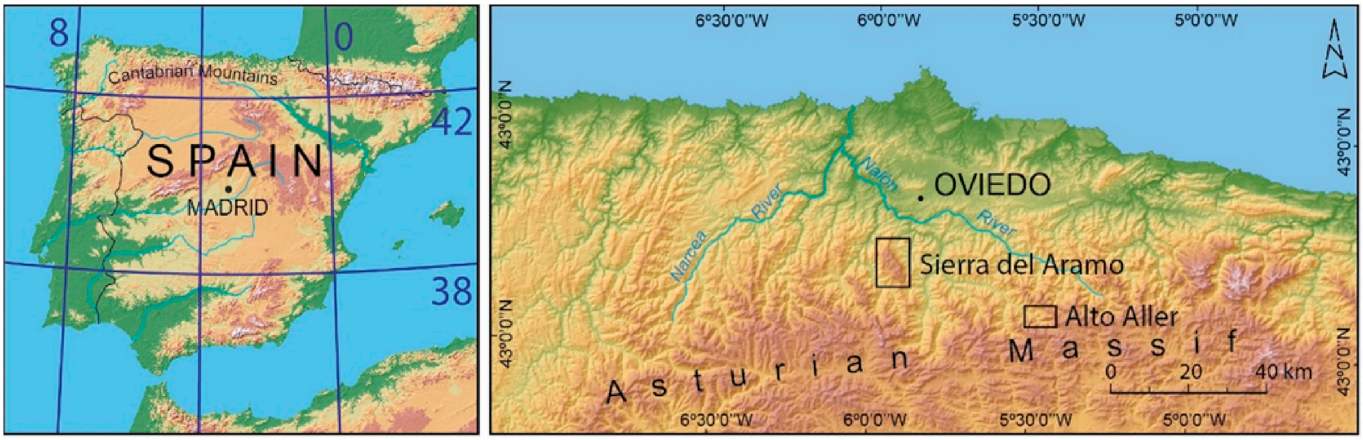

Fig. 1. Location of the study area.

analysing the disturbances that snow avalanches produce in the structure and composition of mountain ecosystems (Bebi et al., 2009), in the increase of biodiversity (Pattern & Knight, 1994; Rixen et al., 2007), and in the regeneration of subalpine forests (Kajimoto, Daimaru, Okamoto, Otani, & Onodera, 2004). There is also research into changes in forest structure as a result of the suppression of the disturbance caused by avalanches (Kulakowski, Rixen, & Bebi, 2006). However, in all this research snow avalanche disturbance on forest landscapes is analysed without considering other relevant factors that have gained importance in recent years, and that interfere decisively in such processes, such as land use change and climate change (Kulakowski, Bebi, & Rixen, 2011; Muntán, 2016; Schläppy et al., 2016). This gap has been partially filled following the publication of recent studies that have revealed the importance of climate warming in the increase of wet snow avalanches in the high mountains (Ballesteros-Cánovas, Trappmann, Madrigal-González, Eckert, & Stoffel, 2018; Naaim et al., 2016). However, the scarcity of data for the Atlantic mid-mountains of temperate latitudes leads to an undervaluation of the repercussions on landscape, heritage and hazards of snow avalanches (Beato Bergua, 2018).

The fundamental objectives of this study, therefore, are to: i) analyse the effects of depopulation and changes in land use in the evolution and structure of the forest landscape in the Asturian Central Massif (Cantabrian Mountains) from 1960 to the present; ii) examine the effects of climate change on snowiness and the formation of snow avalanches; iii) determine how changes in land cover and snow avalanches have finally affected the landscape.

1.1. Geographical setting

The Asturian Massif constitutes the western sector of the Cantabrian Mountains, which run over 220 km parallel to the northern Spanish coast at the NW end of the Iberian Peninsula. Covering an area of almost 18,000 km^2 (Muñoz & Sanz, 1995), the Massif consists of three units: Western, Central and Eastern. The Asturian Massif is made up of Paleozoic carbonate and siliciclastic materials that have been folded and fractured by the Variscan and Alpine orogenies (Aramburu & Bastida, 1995). From the climate point of view, it enjoys typically Atlantic conditions, with mild temperatures and abundant rainfall (1100 to 1500 mm) distributed throughout the year. Muñoz (1982) differentiates three types of climatic variants in accordance with the temperature changes generated by the altitudinal gradient: between 700 and 1000 m asl, there is a Cfsb$_3$ temperate climate in transition to fresh; between 1000 and 1500 m asl there is a truly fresh climate (Cfsc) and finally, above 1500 m asl we encounter a cold, high-mountain climate (Dfsc) with half of the precipitation in the form of snow.

The vegetative cover is characterized by the strong secular anthropization of the territory, and by its belonging to two biogeographic districts of the Eurosiberian Region, the Oviedese and Somedese-Redese sectors of the Cantabrian-Atlantic and Orocantabrian subprovinces, respectively (Díaz, 2014). Therefore, the mid-mountain is defined by potential plant formations dominated by oaks, beech, and mixed deciduous woodlands, as well as by alder and willows along the riverbanks, with birches and holly trees colonizing new spaces and, now in the subalpine zone, by upland scrubs such as creeping juniper.

The mountain landscape presents a mosaic of enclosed meadows, forests, thickets, and open pastures created by a highly diversified, traditional, agro-livestock subsistence economy (Beato Bergua, 2018). There are some towns in the bottoms of the valleys, but the population is distributed among small villages and cottages scattered across the hills. According to the 2016 municipal census, in the 21 mountain municipalities of Asturias there were 61,512 inhabitants (Spanish Statistical Office). This is 6% of the total of the region which yields an average population density in the Asturian mountain of 13.73 h/km^2. In effect, the declining agricultural sector has led to emigration from the mountains to the cities or other industrialized areas, and there has been a genuine rural exodus, an ageing of the population, and a significant change in land use (Serra, Vera, Tullab, & Salvatic, 2014). In addition, beginning in the 1970s the transition occurred to an exclusively cattle-based, semi-extensive, livestock mono-production based on meat and subsidies, and it was then that the surface area of pastures began falling rapidly, with the consequent change in landscapes (González et al., 2018).

For a more detailed study we have focused on the Sierra del Aramo and the Alto Aller. They are two of the main mid-mountains (between 1000–1800 m asl) of the Central Asturian Massif, and are located about 20 km SW (Aramo) and 50 km SE (Aller) of Oviedo, the capital of the Principality of Asturias (Fig. 1).

2. Materials and methods

The methodology consisted in the analysis of geomorphological forms and processes (Butler, 1985; Stoffel, Bollschweiler, & Hassler, 2006), biogeographical inventories (Butler & Malanson, 1985), the review of historical documents such as demographic and socioeconomic databases, and terrestrial and aerial photographs (Lambert, 2009), together with the study of climatic factors (old and recent series) (Teich, Marty, Gollut, Grêt-Regamey, & Bebi, 2012b) and topographic features (aspects, slopes) (Teich, Bartelt, Gret-Regamey, & Bebi, 2012a). The historical records of snow avalanches have been consulted (Sawyer & Butler, 2006). In addition, changes in land use and global warming were analysed because they are the most important factors currently modifying ecosystems and the behaviour of snow avalanches (Bebi et al., 2009; Kulakowski et al., 2011).

2.1. Field data collection

The fieldwork consisted of walking the slopes over several transects, both longitudinal (ascending/descending the previously identified snow avalanche paths) and transversal (crossing the slopes at different altitudes between the starting zones and runout areas), in order to document the envelopes of the snow avalanches and their effects on the forest cover. All uprooted, decapitated or otherwise impacted trees, were identified, inventoried and located by GPS. The forms and processes of nival origin were analysed from the geomorphological perspective, and we were able to identify the presence of a large number of avalanche channels. In addition, we carried out a monitoring based on visual observation since 2010 to collect data for the snow avalanche activity. To this end, we visited the places prone to the triggering of the snow avalanches in the Asturian Central Massif after cold storms and snowfalls.

The transects mentioned were analysed also from the biogeographical point of view, by the performing of herborizations (Arozena & Molina, 2000). More specifically, 50 vegetation inventories were carried out following phytosociological criteria (Braun-Blanquet, 1979) to the yield subsequent vegetation characterization and mapping. In each of these, data were collected regarding the orientation, slope, geomorphological situation, rock substrate, and edaphic characteristics with the help of GPS and cartographic sources (INDUROT, 1994; MAPAMA, 2018; Merino-Tomé, Suárez & Alonso, 2014).

2.2. Photointerpretation and mapping

The geomorphological elements and the land cover identified by fieldwork were corroborated by photointerpretation. We used the 1:30.000 scale, black and white aerial photographs processed in 1980–1986, and the color orthophotos of the 2015 PNOA, both from the Spanish National Geographic Institute (IGN, 2018). The features were subsequently digitized for the design of the cartography. Thus, the information obtained in the fieldwork was incorporated into a geo-referenced database and processed through a Geographical Information System managed by the ArcGIS® software (ESRI, 2012). The GIS has made it possible to perform surface calculations, compare our mapped data with other available digital sources (geological, soils, and vegetation maps) and use the Digital Terrain Model with 5-m grid spacing from the IGN to produce aspect and slope maps (IGN, 2018).

Similarly, we used photointerpretation and GIS for the diachronic comparison of the plant formation cover. The growth of forest cover in the Asturian Massif was obtained by comparing the 1966, 1998 and 2014 forest maps of Spain (currently from the Nature Data Bank of the Government of Spain, also in open data format), while for the Sierra del Aramo and the Alto Aller a comparative analysis was carried out of the 1957 and 1985 aerial photograms (after digitization and restitution), as well as of the orthophotos of the 2015 PNOA (Poblete et al., 2016; Beato Bergua, 2018). Finally, land use changes at the regional level were corroborated by the thematic cartography of the WMS service of the Government of the Principality of Asturias (http://www.sitpa.cartografia.asturias.es/), the Land Cover and Use Information System of Spain SIOSE (IGN, 2014), and the Corine Land Cover (Arozarena Villar, Del Bosque González, Villa Alcázar, & Porcuna Fernández Monasterio, 2006).

2.3. Climate and socioeconomic data

The atmospheric warming in the Asturian Massif and its effects on the frequency and intensity of the snowfall, was analysed through the 1971–2016 pluviometric data of the Genestoso mountain station, provided by the State Meteorological Agency (AEMET). Located at 1170 m asl in the SW of the Asturian Massif, it is the only meteorological station with a series of over 30 years in which the data corresponding to snowfall has been collected. For the analysis of recent trends of snowiness, we have made use of the data from the Aller and Pajares stations (at 750 and 1480 m asl), both provided by the AEMET.

The analysis of depopulation was carried out by consulting the population census records of 1900, 1950, 1960, 1970, 1981, 1991, 2001 and 2011, all of them at municipal scale and from the Spanish Statistical Office (INE, 2018a). The study of the evolution of farming activity was carried out through the analysis of farm censuses from 1962 to 2009 (INE, 2018b).

2.4. Snow avalanches events data

Our study of the episodes of snow avalanches was carried out combining field work (visual observation from 2010) with the photointerpretation of aerial images, together with the consultation of landscape photographs, newspaper archives (La Nueva España and El Comercio) and surveys of the local population. Unfortunately, there is still no dendrogeomorphological study in the Asturian Massif that can shed light on the recurrence of snow avalanches, despite their usefulness and relevance (Stoffel & Hitz, 2008; Muntán, 2016). With regard to newspaper archives, García-Hernández (2018) compiled the data series for avalanches that occurred between 1800 and 2015, resulting in a total of 291 events. However, this research method tends to underreport smaller snow avalanches of that do not affect important infrastructures, or cause injuries or deaths (Sawyer & Butler, 2006). Consequently, we need to view the data from this source with great caution, and as complementary to other data sources. Similarly, surveys of the local population suffer from people's selective memory, although they can provide very useful information. In our case, interviews were conducted in the municipalities of Aller, Morcín, Pola de Lena, Quirós y Riosa looking for data about specific places down which snow avalanches descend, and for the magnitude and year in which these avalanches occurred. The Internet (websites, forums) was also searched for any news about snow avalanche events in the Asturian mountains.

In short, our chronology of events is not homogeneous. Events between 1944 and 2010 were researched using press news items and the data contributed by interviewees, corroborated by the climatic data of the snowfalls. As of 2010, it is based on a visual follow-up after any snowfall.

3. Results

3.1. Depopulation of the mountain areas and changes in land cover

The depopulation of mountain areas in the Asturian Massif began more than a century ago. In this long process we can distinguish one period, from 1960 to 2011, in which there was a very intense decline; the population dropped from a maximum of 136,715 inhabitants to only 68,707 in 2011, a drop of 50.2% with respect to 1960. This process occurred, among other reasons, as a result of the crisis of the traditional system of exploitation which was based mainly on agricultural and livestock activities. In Asturias in 1962 the total number of agricultural holdings was still very high at 118,191. From the sixties onwards, there was a notable loss in the number of agricultural holdings, resulting in the reduction by 2009 to a total of just 22,688 farms, 80.8% fewer than in 1962.

As a result, in the mountain areas of the 4478.37 km^2 Asturian Massif, the surface area of forest cover passed from 111,782.2 ha in 1966 to 190,307.75 ha in 2014, according to forest maps (a growth of 17.5% in 52 years). In contrast, scrubland and pasture underwent a significant decrease in surface area, with a loss of 100,510 ha (a decrease of around 22.4%). In the case of the Sierra del Aramo there has been a drastic reduction in pasture, which has gone from 4396 ha in 1957 to 1884 in 2015, a decrease of 17.22% that has mainly affected the mountainsides. Meanwhile, shrubland has increased 1509.6 ha and forests cover has also grown 2597.13 ha over the same time period (an increase of 17.8%) (Fig. 2).

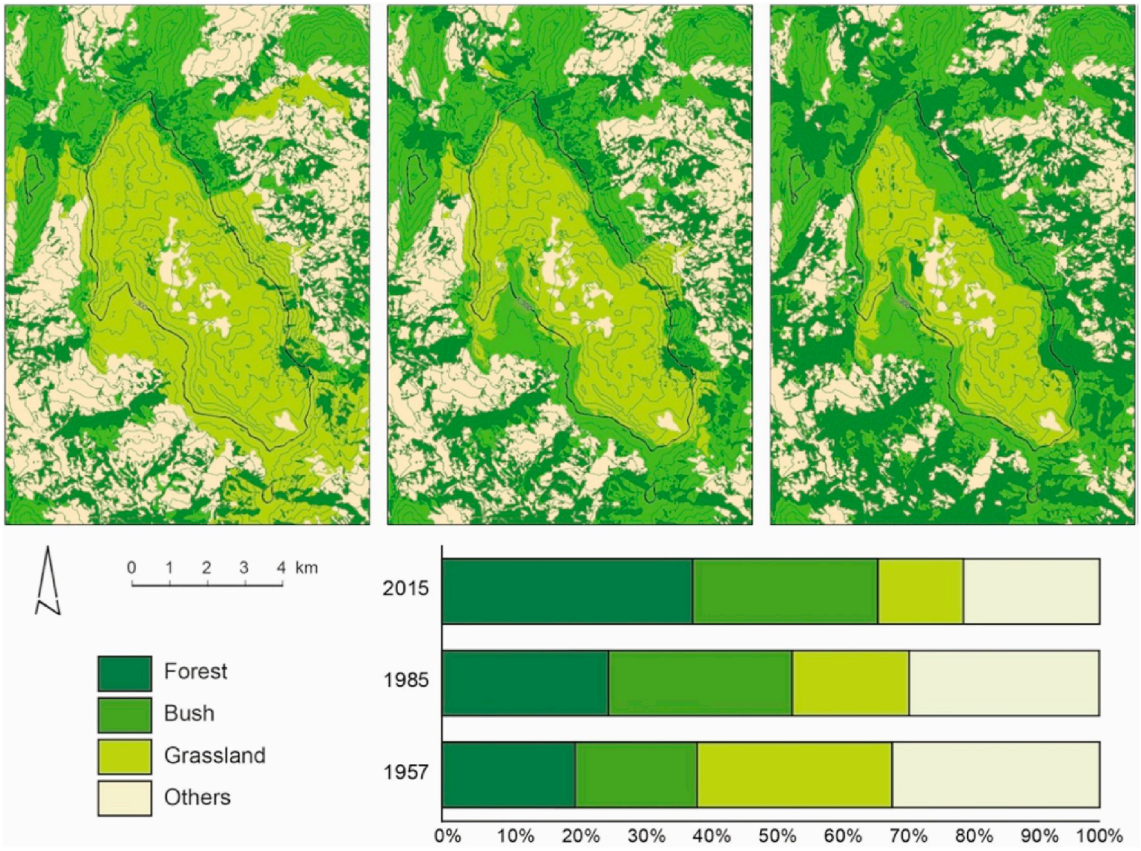

Fig. 2. Current dynamics of the vegetative covers in the Sierra del Aramo.

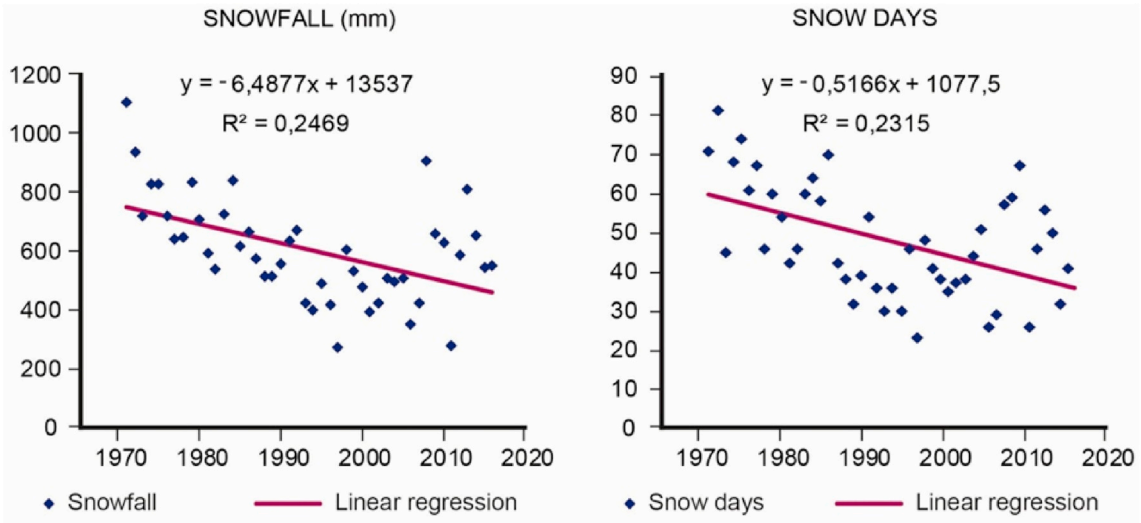

Fig. 3. Decreasing tendency of snowiness in the Asturian Massif from Genestoso meteorological station data.

Forests advance unbroken over areas previously colonized by shrub, and many slopes show a mosaic formed by dense forests (mainly mixed associations of broadleaf tress and beech stands), young forests of birch, maple, and ash, etc., and shrub formations with hazel, sloe, hawthorn, and alder. There are also large extensions of holly (*Saniculo europaeae-Ilicetum aquifolii*) which, benefitting from currently being a protected species, cover clearings that potentially correspond to beech. Finally, different bushes play a leading role in the landscape, forming beds of *Pteridium aquilinum* bracken, mainly accompanied by brambles (*Rubus* sp.pl.), and stands of *Genista hispanica* ssp. *occidentalis,* together with the gorse *Ulex europaeus* or the heather *Erica vagans*. Currently, according to the indicators of the SIOSE and CORINE changes in land uses are decreasing and a certain stabilization is taking place (Beato Bergua, 2018).

3.2. Atmospheric warming and snowiness in the mid-mountains of the Asturian Massif

The most obvious evidence of any change in climate conditions occurring due to global warming, is the study over time of trends in climate variables. For this reason, we analysed the evolution of snowfall from 1971 to 2016 at the Genestoso station in the SW of the Asturian

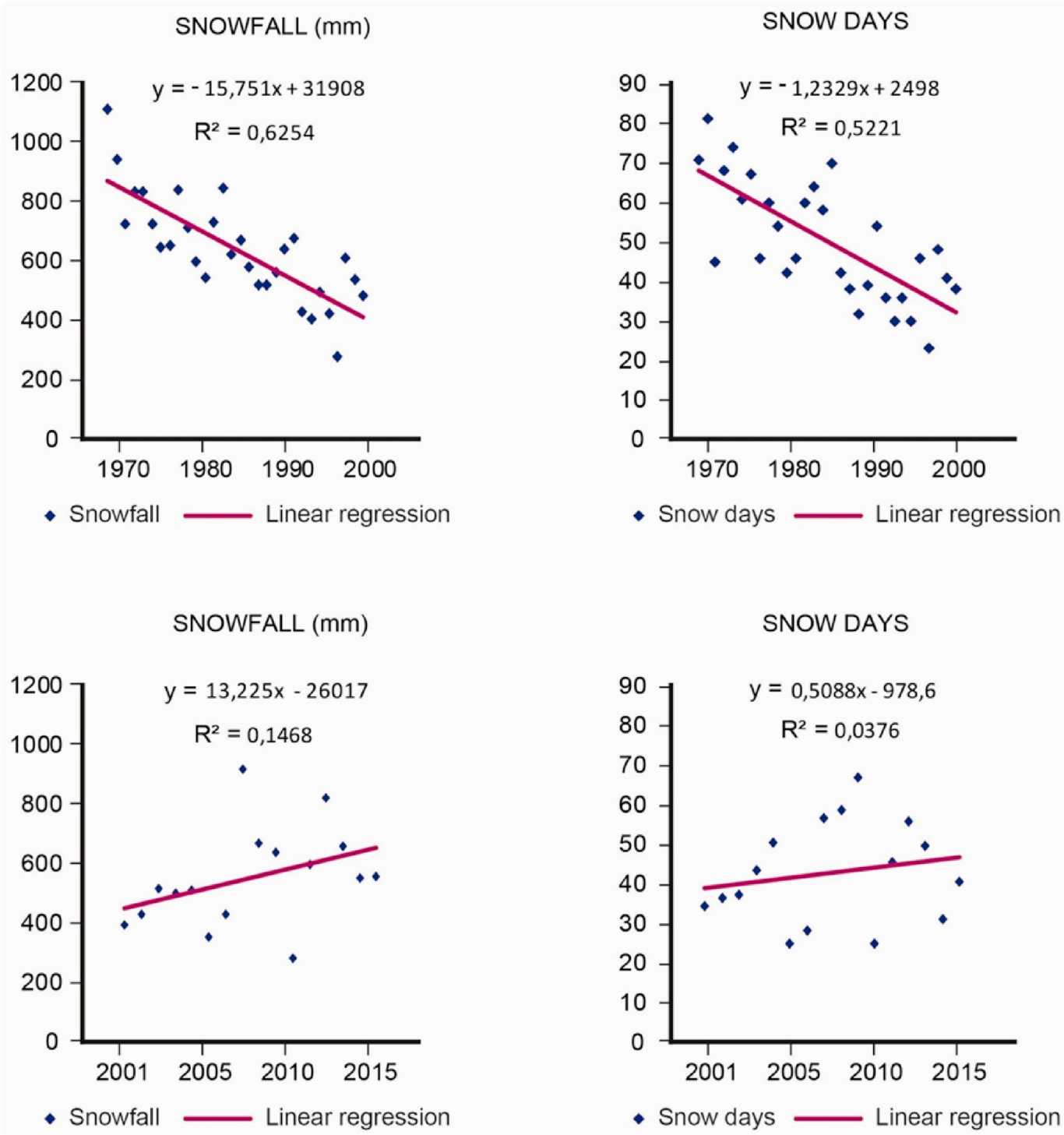

Fig. 4. Historical evolution of snowiness and snow days in two periods (1970–2000 and 2001–2015) from Genestoso meteorological station data.

Massif at 1170 m asl. In this time series, we observed a clear decreasing trend in both the global calculation of snow fallen, and in the number of days when it snows, which has been calculated through linear regression. From 1971 to 2016, snowiness decreased at a rate of 64.8 l/m^2 per decade (Fig. 3), while the number of days when it snowed dropped by 5.1 days per decade.

However, Fig. 4 shows a change in trend in the series from the year 2000 on, making it advisable to divide the complete series into two sections to study them separately. The trend between 1971 and 2000 has a more precise adjustment (R^2 = 0.6254) and the slope is much more marked, with a decrease in snowfall of 157.5 l/m^2 per decade, and a drop in the number of days it snowed of 12.3 days per decade. In contrast, although the series is short, between 2001 and 2016 there is an upturn in snowiness, with an increase in precipitation in the form of snow of 132.25 l/m^2 per decade, and an increase in the number of snowy days of 5 days per decade (Fig. 4).

Despite this upturn (which should be treated with caution given the limited length of the series), snowfall and the number of snowy days has declined significantly if we compare the periods 1971–2000 and 2001–2016, from an average of 634.88 l/m^2 and 50 days to 544.5 l/m^2 and 43.4 days, respectively. In addition to the variability of snowfall values between 2001 and 2016, we have also been able to document

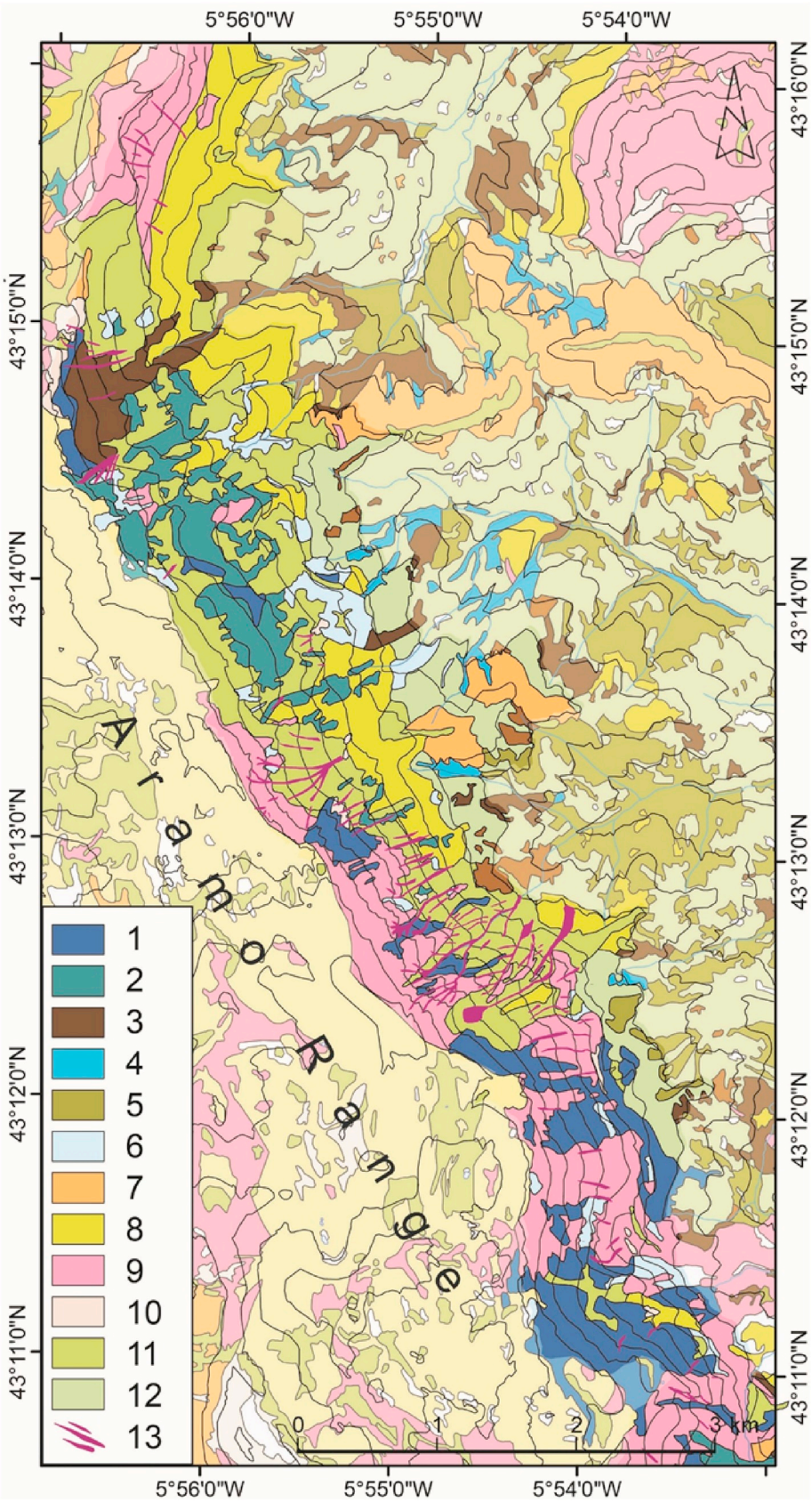

Fig. 5. Vegetation map of the Sierra del Aramo eastern hillside with snow avalanches. 1. Beech wood. 2. Holly bush. 3. Deciduous mixed forest. 4. Riparian forest. 5. Chestnut tree forest. 6. Deciduous bush. 7. *Erica* and *Ulex* shrubland. 8. Fern shrubland. 9. *Genista* low shrubland. 10. Casmophitic vegetation. 11. Grassland. 12. Meadows. 13. Documented snow avalanches.

Fig. 6. A) View of a part of the El Espinial avalanche track in the Sierra del Aramo. B) Avalanche tracks of medium size in the Alto Aller.

that in recent years snowfall has taken place in a highly concentrated and copious manner, occurring in episodes in the order of 5–6 days, and with intensities that occasionally exceed 30 l/m^2 in 24 h. Significant examples of this are the episodes that have occurred over the last three years at the Aller meteorological station (located in the Central Asturian Massif at only 750 m asl) with 5–6 day episodes of snowfall, totals of between 99 and 145.8 l/m^2 of snow fallen, and individual days exceeding 40 mm (data collected daily and by hours from the AEMET). Such snowfalls, the result of successive storms of humid, polar air coming in from the N and NW, produce important accumulations of snow.

Although there is a clear decreasing trend both in the total amount of snowfall and in the number of days of snow, snowiness occurs in very concentrated episodes, and with high intensity. This favours the formation of very significant snow mantles (more than one meter thick at barely 1000 m asl) and, without a doubt, the unleashing of snow avalanches; the classic criterion for defining avalanche scenarios is to take the values of snowfall in previous 72 h as a measure of the thickness of potentially mobile snow (Burkard & Salm, 1992).

3.3. Snow avalanche activity and its effects on the structure and distribution of the forest cover

The depopulation of the Asturian Massif and the crisis of traditional farming and livestock farming systems, has favoured the growth of thickets and forests across the territory. However, this recovery has not occurred on all the slopes under study here. Some of them present an evident forest anomaly, given the predominance of pastures. The cause of this slowing down in the expansion of the forest in these areas is the intense disturbing activity of snow avalanches. Thanks to their great morphogenetic capacity, these can prevent the regeneration of the forest, and can model avalanche paths (Fig. 5).

Indeed, one of the most remarkable geomorphological features of the Asturian mid-mountains is that they are crossed by numerous avalanche tracks. In general, the tracks start at the exit of snow hollows, and adopt a rectilinear arrangement with an internal structure in the form of a slide, whilst forming small screes, or even large cones of blocks and debris, in the arrival zone. Small tracks have also been modelled in the rocky, upper outcrops, which either open out or join other tracks lower downhill, thus promoting the accumulation of screes. We have identified a hundred avalanche tracks in the eastern slope of the Sierra del Aramo, for example, which has an area of approximately 1554 ha, and these are still active due to the recurrent character of snow avalanches. Some of these tracks, such as Reguerón, Arguixu La Yampa and El Espinial, can be classified as 'large' because they are more than 1000 m long (McClung & Schaerer, 2006) (Fig. 6). However, the average length of these tracks is 286.5 m long, making them medium-sized, between 100 and 1000 m (McClung & Schaerer, 2006).

The triggering of snow avalanches in the Sierra del Aramo basically responds to three main factors: the intense snowfall, the leeward orientation to the predominantly N and NW storms, and the steep slopes. These factors are responsible for the triggering of avalanches in the whole Asturian massif (Marquínez et al., 2003; Wozniak & Marquínez, 2004) and especially in the mid-mountains (Poblete et al., 2016). Throughout the year there are about 4 or 5 snow storms between October and April. These periods are followed by others with mild temperatures, even in winter, due to climate warming. The other factor that explains the activity of snow avalanches is the angle of the eastern slope of the Aramo. 52.26% of the slope analysed is at an angle prone to avalanche formation, that is, between 30 and 50°. If we exclude the area below 1000 m asl from the analysis, the figure rises to 63%. Slopes steeper than 50° barely reach 6.6% of the total area, though they mainly coincide with starting zones. These data take on their true significance when we remember that the Aramo is a medium altitude mountain, and that only 9.7% of the mountainside lies above 1400 m. This is precisely the altitude where the starting zones of the most outstanding snow avalanches lies, although there are also starting zones even below 1100 m. Finally, the runout areas in the most dynamic sector go down as low as 700 m asl.

Two types of snow avalanches are triggered most frequently down the slopes under study: on the one hand, wet snow avalanches that move slowly channelled in by the avalanche tracks, and on the other hand, sluffs in the form of dry snow flows. The latter occur in the sections with slopes greater than 50°, at higher speed, and with less impact. The wet snow avalanches have a greater destructive capacity and are responsible for the removal of larger trees, which are uprooted and dragged downhill. In contrast, the sluffs are faster and carry out mutilating work, uprooting branches and decapitating the tops of trees and shrubs (Figs. 7 and 8).

Snow avalanche events have occurred annually since 2000 on paths with starting zones situated above 1400 m asl. In contrast, the starting zones below 1400 m asl are not sufficiently fed every year (Table 1), and so the 100 documented tracks are not continuously active. The greatest activity occurs in the central paths in which wet snow avalanches occur with a frequency of 3 events per year.

The analysis of historical sources provides interesting results. Interviews with locals reveal the dates of historical snowfalls. Although all the interviewees confirm the intense, continuous activity of snow

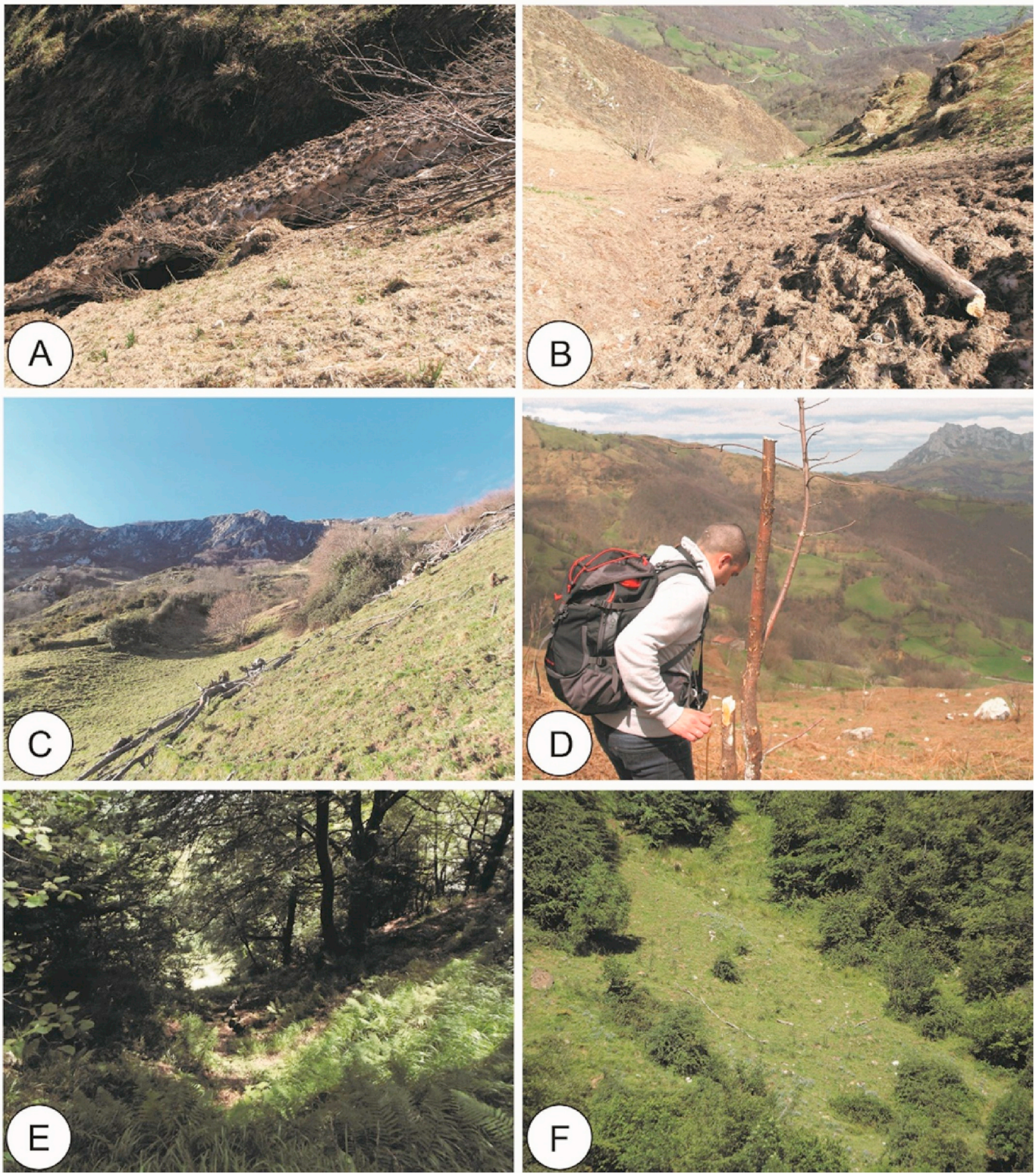

Fig. 7. Damaged trees on the Sierra del Aramo eastern hillside. A) Remains of wet snow in El Reguerón avalanche track. B) Trunk and branches on remains of wet snow in the same track. C) Beech trees uprooted by avalanches in Chiechariego. D) Decapited tree by sluff avalanche. E) Snow avalanche path into the forest cover, with broken branches and trees uprooted at the headwater of the Morcín basin. F) Boulders deposit with remains of broken trees in the runout zone of a forest avalanche path in Fonfría.

avalanches, they also indicate that nowadays it snows less often. In 1888 the snow avalanche of the Reguerón descended below 600 m (1,54 km in length) and destroyed an old hydraulic mill in the Code valley. The years 1945, 1954, 1956, 1957, 1971 and 1972 are remembered as very active. A 1976 photograph shows several snow avalanches running down the slope. On the other hand, the only press news that exists refers to 2007. The interviews also reveal that in the last decade there has been a concentration of snowfall over a few days

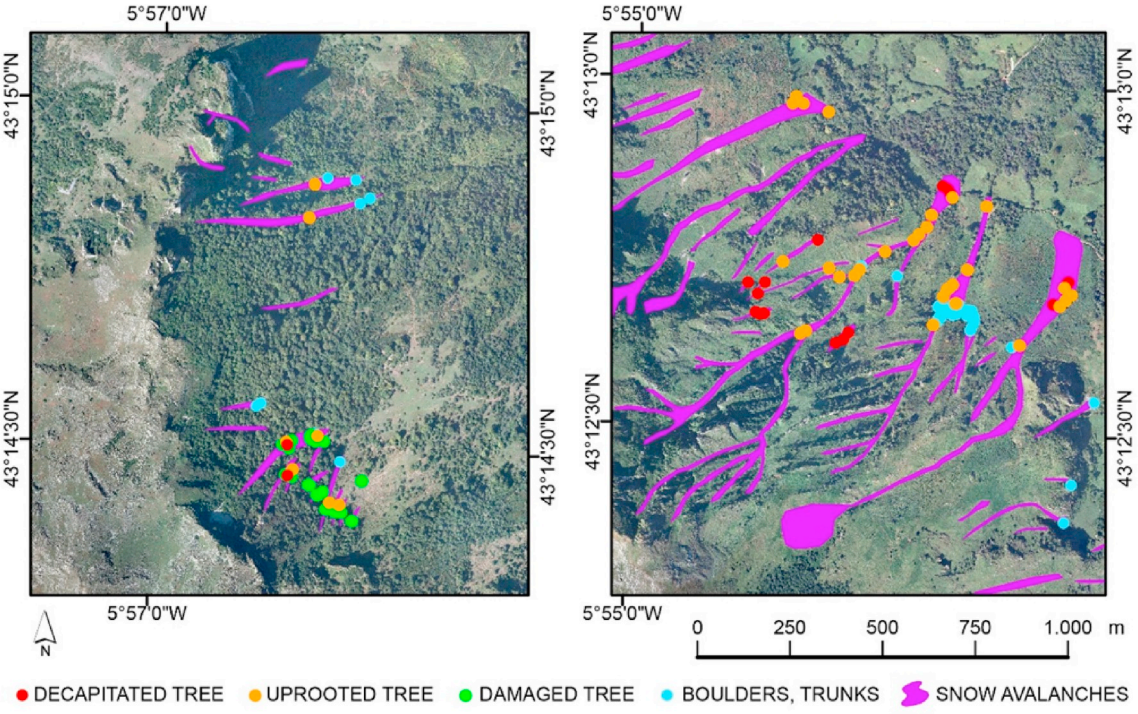

Fig. 8. Mapping of trees affected by snow avalanches made of GPS data in two slopes of the east side of the Sierra del Aramo.

Table 1
Dates of snow avalanche events from 1944 to 1945 to 2017–2018 in the Asturian Massif.

	Historical archives and meteorological sources														
	1944 1945	1945 1953	1953 1954	1954 1956	1956 1957	1957 1958	1958 1971	1971 1972	1972 1974	1974 1975	1975 1979	1979 1980	1980 1984	1984 1985	1985 2000
1															
2															

	Historical archives and meteorological sources										Fieldwork							
	2000 2001	2001 2002	2002 2003	2003 2004	2004 2005	2005 2006	2006 2007	2007 2008	2008 2009	2009 2010	2010 2011	2011 2012	2012 2013	2013 2014	2014 2015	2015 2016	2016 2017	2017 2018
1																		
2																		

Activity of snow avalanches that have their starting zones located above 1,400 m asl (1) and below 1,400 m asl (2). The upper chart shows the dates obtained from historical archives and meteorological sources until the 2000 year. The lower chart shows the dates recently obtained also from fieldwork. Dark grey squares correspond to major avalanches events and light grey to smaller avalanche events.

Table 2
Vegetative cover zonation in the avalanche tracks.

	Morphology	Vegetative cover	Species	Other vegetation
Starting zones	Snow hollows and rocky escarpments (sub-vertical calcareous outcrops)	Rupicolous vegetation	*Saxifraga paniculata, Saxifraga trifurcata, Asplenium trichomanes* subsp. *quadrivalens, Campanula arvatica* subsp. *arvatica, Globularia nudicaulis*	*Fagus sylvatica, Betula celtiberica, Salix caprea, Taxus baccata* and *Sorbus aucuparia* are also developed in isolation or in small stands
	Summit areas with some edaphic development	Closed formations dominated by *Genista hispanica* ssp. *occidentalis* and *Erica vagans*	*Genista legionensis, Carex brevicollis, Lithodora diffusa, Euphorbia flavicoma, Koeleria vallesiana, Hippocrepis comosa*	Some shrubby specimens of *Corylus avellana, Sorbus aria* and *Rhamnus alpina*
Tracks	Regularized surfaces Paths with edaphic cover	Meadows	*Cynosurus cristatus, Lolium perennial, Trifolium repens, Trifolium pratense, Plantago media, Merendera pyrenaica, Phleum bertolonii, Nardus stricta, Danthonia decumbens, Poa pratensis* and *Poa trivialis*	
	Paths with debris deposit	No vegetation		
Runout zones	Deposits with edaphic cover	Meadows	*Linum bienne, Gaudinia fragilis*	Shrub formations, mainly *Pteridium aquilinum* and *Rubus* sp.pl. with scattered specimens of *Ilex aquifolium, Corylus avellana* and *Betula celtiberica.*
		Disused grasslands	*Brachypodium pinnatum* ssp. *rupestre, Bromus erectus,* or *Carex brevicollis* with *Helianthemum nummularium* and *Teucrium pyrenaicum*	
	Debris deposits	No vegetation		Rupicolous vegetation, specimens of *Corylus avellana*

and several events of snow avalanches. This coincides with the climate analysis and other studies of a regional nature (García-Hernández, 2018).

The disturbing effects of snow avalanches have an impact on the distribution and structure of the forest cover. In the mid-mountains of the Asturian Massif, they are another factor for deforestation, and not only that of the tracks. Indeed, an ample section of the range's southern slopes located between 700 and 1600 m asl and covered by herbaceous plant formations, should be colonized by a dense forest mass, especially if we consider the rapid natural regeneration that has taken place in the Asturian mountains. In marginal areas where small forests have historically been preserved, snow avalanches are channelled under the tree cover, favouring the opening of linear corridors in which the herbaceous stratum also predominates. However, the taxonomic or floristic composition of the forest belt has not been altered by snow avalanches.

The avalanche starting zones, which coincide morphologically with snow hollows or with rocky escarpments, correspond to sometimes subvertical calcareous outcrops where rupicolous vegetation develops adapted to the cracks in the rocks (Table 2). On the other hand, a common feature of the avalanche tracks is a meadow vegetation cover. This develops from the foothill zone upwards as far as the initial stretch of the subalpine zone. In addition, different shrub communities are now making progress across the mountainside due to lower livestock pressure. These clearly delimit the areas through which avalanches occur and consist basically of the fern and brambles. Finally, in the avalanche runout zones we predominantly find an intercalation of pastures and grazed meadows with disused grasslands. There are also areas colonized by shrub formations, with scattered specimens of trees. In this case, the landscape offers a desolate aspect since it appears to be covered by large blocks and ridges, destroyed arboreal remains and damaged shrubs.

4. Discussion

The transcendence of snow avalanches, both in intensity and frequency, in the mid-mountains of the Asturian Massif is not limited only to the Sierra del Aramo or the Alto Aller. It occurs in all mid-mountains in the range situated between 1000 and 1800 m, and with slopes between 30° and 50°. More specifically, snow avalanches affect 173.15 km^2 (9.6%) of the mid-mountain area of the Asturian Massif (Fig. 9), and around 19 mid-mountains affected by snow avalanches have been identified by various authors (Table 3).

To the multiple ecological functions that forests perform on the mountain slopes, we must add the important protective work of preventing the formation of snow avalanches (Gubler & Rychetnik, 1991; Schneebeli & Bebi, 2004), of decreasing runout distances (Anderson & McClung, 2015; Takeuchi, Torita, Nishimura, & Hirashima, 2011; Teich et al., 2012a), and of mitigating the impact of snow avalanches on buildings and infrastructures (Brang et al., 2006). This protection work comes about through the reduction of the speed and energy of avalanches, especially in the case of small avalanches (Schneebeli & Bebi, 2004), as well as those that occur within the forest, known as forest avalanches (Teich et al., 2012b). On the other hand, we have to take into account that since the second half of the 20th century, as a result of the change in land use and the abandonment of the traditional exploitation system, there has been a spontaneous regeneration of forests, which have experienced a remarkable expansion in European mountains such as the Alps (Gellrich, Baur, Koch, & Zimmermann, 2007), the Pyrenees (Vicente-Serrano, Lasanta, & Romo, 2004), the Carpathians (Kozak, 2003), and the Cordillera Cantábrica (Bengoa, 2011). Because of this, it would be logical to assume a reduction in the number of snow avalanches in these mountainous regions. However, reforestation has not occurred equally on all slopes, as those receiving more sunlight have been more deforested, and the impact of snow avalanches has been greater, an impact that also depends on the underlying lithology and, more fundamentally on the intensity of the slope. In fact, Bebi

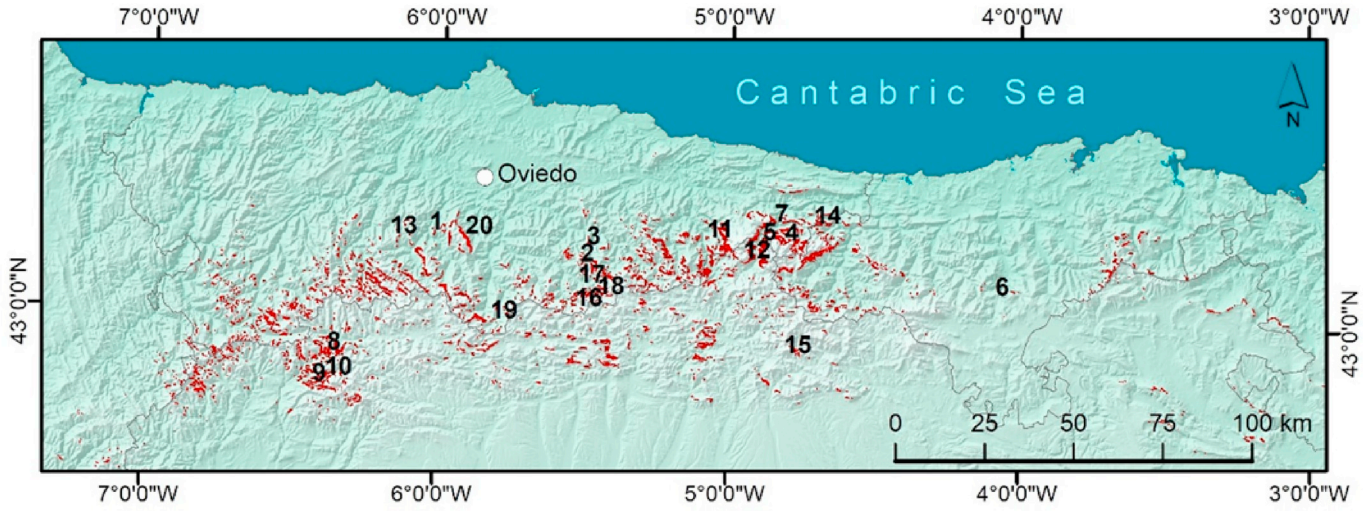

Fig. 9. Mid-mountains prone to triggering snow avalanches in the Cantabrian Mountains (1000–1800 m altitudes with 30–50° slope, in red). The numbers correspond to the references listed in Table 3. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Snow avalanches in mid-mountains of the Asturian Massif (mentioned in papers).

Publication	Range	Starting zone (m)
Castañón (1986)	1) Sierra de Tene	850
Marquínez et al. (2003)	2) Retriñón	1862
	3) Moroma	1658
González (2007)	4) Peña Maín	1606
	5) Murallón de Amuesa	1446
Martínez and Serrano (2008)	6) Alto Besaya	800
Ruíz et al. (2008)	7) Sierra de Portudera	1343
Santos et al. (2010)	8) Miro de Tejedo	1800
	9) Valseco	1670
	10) Braña de la Turria	1800
González and Serrano (2011)	11) Valle del Dobra	1700
	12) Valle del Cares	1654
Rodríguez (2011)	13) Sierra de Santa Cristina	1369
Hernández (2014)	14) Sierra de Cocón	1508
Serrano et al. (2016)	15) Alto Carrión	1860
Poblete et al. (2016)	16) Bailaderu el Oso	1568
	17) Peñas Agúa	1633
	18) Sierra de Valverde	1800
García-Hernández (2018)	19) Pajares	1868
Beato, Poblete & Marino (2018)	20) Sierra del Aramo	1791

et al. (2009) have shown that forest expansion is only relevant when limiting the formation of snow avalanches in certain topographic conditions, and its protective role in forests located on very steep slopes can be discarded.

In the Asturian Massif, García-Hernández et al. (2017) point out that natural reforestation has contributed to the reduction of the damage caused by snow avalanches. However, although it may seem paradoxical, they indicate that tendency in the number of damaging avalanches does not decrease, since the highest percentage of years with damaging avalanches (48%), and the highest percentage of years recording more than five events (13%), are recorded precisely in the stage 1960–2015. Either way, in the Asturian Massif the reduction of the damage derived from snow avalanches in no way establishes a decrease in the threat and hazard of snow avalanches, especially in middle mountains. The reasons for their highly hazard nature are: the average size of the avalanche paths, which is between 300 and 400 m (Marquínez et al., 2003); the predominance of wet snow avalanches (Castañón, 1984; Wozniak & Marquínez, 2004); the fact that snow avalanches take place around 200 m above the treeline. The avalanches in the Asturian Massif are frequent and occur predominantly over steep, highly deforested southern slopes, traversed by infrastructures such as roads, railways and mountain paths that cross the avalanche tracks. We also need to bear in mind the intense sports use of the mountain areas (cross-country skiing, mountaineering, hiking, etc.), plus the fact that protective measures against avalanches such as snow sheds and snow nets are both scarce and relatively recent, the oldest dating from 2008 (Poblete et al., 2016). In fact, Wozniak and Marquínez (2004) point out that 21 sections of regional, district and local roads are periodically damaged or cut by avalanches in the Asturian middle mountains.

The effect of climate change on the intensity and frequency of snow avalanches is currently the subject of analysis and debate among researchers. The effect is little known (Teich et al., 2012b); a decrease in runout elevation has been observed (Eckert, Parent, Kies, & Baya, 2010), together with an increase in the relative proportion of wet snow avalanches (Ballesteros-Cánovas et al., 2018; Martin, Giraud, Lejeune, & Boudart, 2001; Naaim et al., 2016). Whatever the case, it is very difficult to generalize or reach valid conclusions, since the frequency and magnitude of snow avalanches could increase or decrease depending on elevation and on ecological changes (Bebi et al., 2009).

The climate of the Asturian Massif, as with the rest of the planet, has experienced a progressive increase in temperature that has intensified since the 1980s. Álvarez et al. (2009) have shown a constant and homogeneous increase in atmospheric temperature, which has been more pronounced in spring and summer. The increase has especially affected maximum temperatures, leading to an average increase of 0.21 °C per decade over the period 1961–2007. Although in the middle mountains of the Asturian Massif, there is a decrease in the number of days and in the volume of snowfall in general, snowfall is copious and occurs in concentrated events inserted into periods of mild temperatures. When followed by rain or the arrival of warm air, wet snow avalanches are easily generated, and these are beginning to occur more and more frequently because this favour the generation of unstable snowpack structures (Jamieson, 2006; Muntán et al., 2009). If these copious and concentrated snowfalls are also produced on deforested slopes subjected to high radiation because of theirs easterly and southerly orientations, and with slopes steeper than 30°, it is easy to conclude that snow avalanches will continue to be frequent and highly hazardous. Consequently, it is necessary to better understand the relationship between the natural and cultural phenomena that are taking place in the Atlantic mountains, to address territorial, landscape, and heritage changes, and the possible associated risks. In this respect, this study provides new data on the changes in precipitation in the form of

snow, corroborates a land-cover change due to the depopulation of the rural environment of the Asturian Massif, and exposes the importance of field work to detect threats that can be underestimated, such as the snow avalanches in the middle mountains. General statements such as "reforestation decreases the danger of snow avalanches" or "climate change reduces the impact of snow avalanches" may underestimate what happens on a local scale, with negative repercussions for society.

5. Conclusions

The natural regeneration of the forest cover in the Asturian Massif (beginning in the 1960s as a result of the substitution of a system of agroforestry overexploitation for another based on the abandonment of the land and semi-extensive marginal exploitation) is a fact that is clearly reflected by the expansion the forest by 78,525.55 ha. However, the expansion of the forest does not occur homogeneously over all slopes and at all altitudes. Among other reasons, this is because reforestation depends not only on socioeconomic factors, but on natural ones, too. Among these are the climatic conditions (and changes in these due to global warming), and of course, the present-day dynamics of the slopes where the disturbing activity of snow avalanches plays a relevant role.

Changes in atmospheric conditions in the Asturian Massif have increased since the 1970s. This has led to a change in snowiness (a decrease in the total amount of snowfall and in the number of days of snowfall) accompanied by a change in its behaviour (copious snowfall concentrated into storms lasting several days). However, this has not led to a decrease in snow avalanche activity, which maintains high levels of frequency and intensity.

In effect, both dry and wet snow avalanches are partly responsible for the deforestation currently suffered by the Atlantic middle mountains, especially on eastern and southern slopes. The abundant snowiness concentrated over various storms between January and March, together with the presence of steep slopes, brings about the annual recurrence of snow avalanches whose intense destructive capacity has prevented spontaneous forest regeneration, whilst also being responsible for the formation of substantial pastures.

This paper corroborates the usefulness and effectiveness of studies of the interactions between vegetation and snow avalanches whilst also considering the repercussions derived from changes in land use, and from climate change. In short, research conducted from an integrated perspective provides valuable information that can improve our understanding of the dynamics and evolution of forest landscapes, a factor that is fundamental for correct and proper territorial planning and management.

Declarations of interest

None.

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